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PRINCIPLES OF THE CURTAILMENT OF SOURCES OF COMMAND SIGNALS IN MULTIFUNCTIONAL BIOELECTRIC CONTROL SYSTEMS

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ABSTRACT. Bioelectric control systems for several slave mechansims using a single muscle are discussed.

Motor, as well as bioelectric, components are of practical interest for use /128 as control signals in the man-machine system, because they reflect the degree of muscular tension and, in the final analysis, characterize the motor components of motion. Bioelectric control systems (BECS) can be used for this purpose, and in fact are used today in different branches of medicine and engineering [1-3].

The simplest form of a BECS can be realized when the signal source is just one muscle (a single-channel control system).

In fact, however, a greater number of control muscles is required to control devices that functionally resemble the motions of the individual parts, or the entire extremity, of man. A two-channel control system, in which each muscle would control the corresponding direction of motion of a reversible slave mechanism (SM), is needed, for example, to control the closing and opening of the fingers of an artificial hand, the pronation and supination of the hand, the flexion and extension of the forearm in the elbow joint, and other movements of the prosthetic device. This is where proportional and relay control principles have found application [4, 5].

But one degree of freedom is not enough to carry out the most widely used functions. The system must be given greater functionality by introducing additional pairs of controlled movements. And this gives rise to the task of making a rational selection of the control system design, the timeliness of which will constantly improve by virtue of the increase in functionality. This is where the different principles involved in the building of bioelectric control systems can find their application.

The principle most widely used in the building of a BECS is that in which each pair of muscles controls its own SM, regardless of the condition of the other muscles, and yet has no influence of the operation of the other SM. Systems

such as these provide control of all movements simultaneously, in sequence, or in any combinations. Systems such as these can be called independently (simultaneously) controlled bioelectric systems. But the number of channels will increase in proportion to the increase in the number of movements controlled, and the control system will become unwieldy. /129

Information can be transmitted from several sources over one channel by using a variety of coding methods; frequency, or time, for example. Coding in terms of the level, or shape, of the control signals is virtually impossible without the use of special, complicated converters, so amplitude and frequency curves for the biopotentials of the different muscles are commensurate [6-9].

The use of systems with independent control creates additional problems with respect to the selection and training of several independently contracting muscles, the number of which in a healthy extremity, to say nothing of an amputated, or paralyzed one, is limited. And if, in addition, one takes into consideration the technical difficulties associated with system unwieldiness, as well as some of the biomechanical peculiarities of motor acts, a whole series of which are performed in a time sequence, rather than simultaneously, one can conclude that the use of systems with independent control is not always desirable.

We can, by using a variety of coding methods, reduce the number of channels, as well as the number of control signal sources (muscles), without reducing the number of SM. Systems such as these, which provide what is basically sequential control of SM, can be called dependent sequential control systems. Here the required movement cannot be controlled until the corresponding SM is connected into the system. This requires the insertion of logic switches (LS) controlled by special commands. These are switching commands, as distinguished from SM control signals, but they can be transmitted over the same channels that carry the SM control signals, or over special channels.

The fact that the operator has broad scope in changing amplitude, time, and speed parameters of the biopotentials as he desires make it possible to use a wide variety of coding methods. A switching code in terms of one of the biopotential parameters noted is a parametric code (amplitude, speed, for example). An amplitude code can be discrete, and continuous, with switching in the former

the result of discrete contraction of the muscle, and in the latter the result of a continuous signal supply. A discrete code controls an LS with two and more stable states, or an LS with one stable state and a time relay. The control and switching signals will differ on the time line. This requires additional switching time.

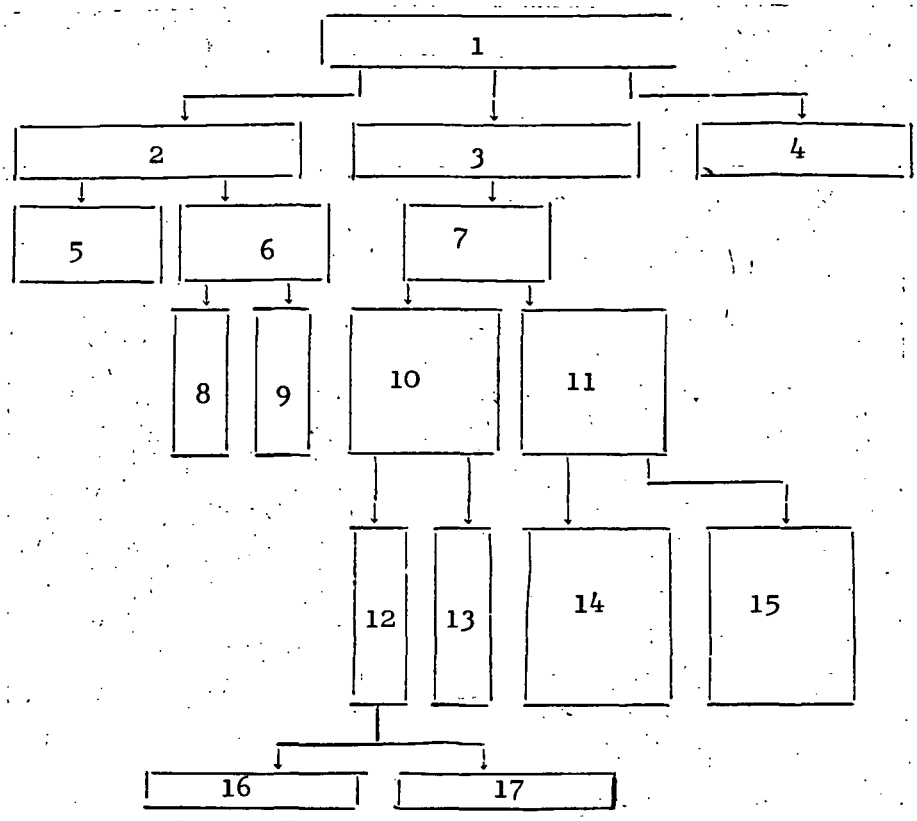
A continuous code controls an LS with one, and more stable states. Here the switching of the corresponding SM takes place only while the continuous signal is being supplied. Consequently, there will be no difference on the time line if the switching and control signals are transmitted over a common channel.

Combination codes, which are a temporal combination of parametric codes for the signals from one muscle (a Morse-type code), or a combination of parametric codes for signals from different muscles, are possible and differ from the parametric code that uses single signals.

It is desirable to try to use a universal control system, one like the central nervous system, to control rather complicated technical devices and, in particular, to use the program developed by the central nervous system for controlling motor actions. These programs can be selected with the help of the biopotentials occurring in the muscles. This principle can be characterized by selecting a "bioelectric image" the use of which will result in the control signals determining the instantaneous conditions of a series of muscles taking part in natural movements (see the classification diagram). /130

Let us consider the very simple method for controlling a reversible SM by signals from but one muscle. Muscles perform two functions in this case, control and switching.

A system with relay control and amplitude selection of the command signal is an example of a system with a parametric switching code without time separation of the control and switching signals, and is one in widespread use today. Figure 1 is the block diagram. Signal voltage is amplified by amplifier 1 and fed into integrator 2, then to the level decoder 3. The signal then is fed into the corresponding power amplifier, 4 or 4', depending on signal amplitude. The loads are electromagnet relays. Relay operation (R_1 or R_2) connects the electric motor



Key: 1 - Bioelectric control system (BECS); 2 - independent (simultaneous) control; 3 - dependent (sequential) control; 4 - bioelectric image; 5 - without communication channel consolidation; 6 - with communication channel consolidation; 7 - switching codes; 8 - frequency; 9 - time; 10 - parametric; 11 - combination; 12 - amplitude; 13 - speed; 14 - combination of parametric codes for 1st muscle; 15 - combination of parametric codes for different muscles; 16 - discrete; 17 - continuous.

to the supply with the required polarity. Other countries are developing similar control systems, Scott in Canada [13], and Trombly et al. in the USA [14].

The command signal amplitude selection principle has spread to proportional continuous and pulse systems [10-12].

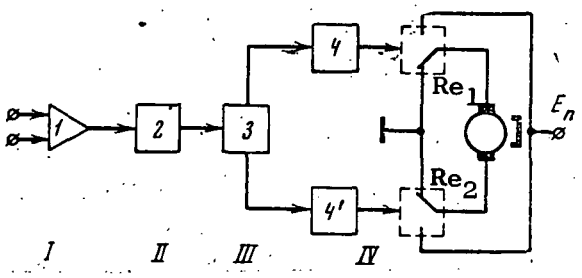


Figure 1. Block diagram of a relay control system with command signal amplitude selection. I - biopotential amplifier; II - integrator; III - level decoder; IV - power amplifier.

The amplitude code system without control and switching signal separation requires no additional switching time, but the dynamic regulation range (in the case of the proportional system) is much contracted.

The control system using signals from one muscle can use an amplitude,

as well as a speed, code without time separation of control and switching signals. This will be a proportional-relay system. The system will regulate the /131 speed so it is proportional to the input signal for one direction of rotation of the SM, but only relay control will be exercised for rotation in the other direction.

The use of a parametric code (amplitude or speed) with time separation of the control and switching signals sometimes is desirable. Time separation in this system permits the use of the full dynamic range of the input signal to regulate speed in each of the directions of SM movement.

Figure 2 is the schematic diagram of a proportional system using a speed code with time separation of control and switching signals.

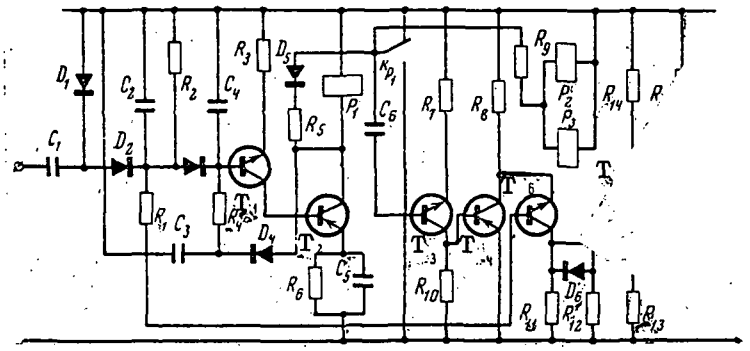


Figure 2. Schematic diagram of a proportional system with a speed switching code.

The biosignal for controlling an SM in one direction is amplitude amplified by a preamplifier, and then fed into an integrator (C_1, C_2, D_1, D_2, R_2), controlling a multivibrator (transistors T5, T6, T7). The pulses, now amplified in power (T8), are supplied to the SM motor.

The operator, in order to switch motor windings, sharply contracts his muscle and thus supplies a single signal which is amplified by a current amplifier (transistors T1, T2), connected in turn to a speed decoder (resistor R_6, capacitor C_5) and causes relay Re_1 to function. Switching of the movable contact of relay Re_1 from the supply minus to plus has the following result.

1. Relay Re_1 must be blocked (by diode D_5 and resistor R_5) in order to hold /132 the relay in the working condition while the control signal changes from the response threshold to the maximum (that is, to the level providing maximum slave

mechanism speed of movement).

2. Relays Re_2 and Re_3 operate. Their movable contacts change the polarity with which the electric motor is connected to the control channel output.

3. The sharp voltage drop across resistor R_8 delays the multivibrator for from 0.5 to 1 second (by the time required for capacitor C_6 to discharge through the circuit of transistors T3 and T4). This is done to avoid any sudden, involuntary movement of the slave mechanism.

4. Relay Re_1 becomes operative through D_5, R_5, and D_4 of the time delay network (C_3, R_4) when there is no control signal. This network is required because of the delay in operator reaction.

Change in control signal amplitude in the range of say 20 to 100 μV thus will result in a proportional change in the speed at which the slave mechanism will move in a straight line. A single sharp contraction of the muscle will cause the electric motor to switch. The switching cell delay time is 0.5 to 1 second. The operator should begin to exercise control in this period of time. He can exercise control upon entering the zone equal to, or exceeding the multivibrator response threshold (20 μV). Should the operator fail to begin control in this period of time the system will automatically return to its original state; that is, to the state of readiness to control movement in a straight line. The operator, upon finding it necessary to reverse the movement at once and at high speed, keeps the muscle in the tensed state for from 0.5 go 1 second after sending a switching signal and then begins to exercise control once again.

If the switching systems just described use a single parametric code, one based on either amplitude or speed, the combination of parametric codes is a combination code that can be used to control a great many SM by using the signals from one muscle. An amplitude code can be used, for example, to control the reverse operation of the SM, while the speed code can be used to connect one of two SM to the system. At the same time (a) the control and switching signals can be separated on the time line, in which case the control system can be of the relay type, or of the proportional type, with a full dynamic range, (b) some of the control and switching commands can be separated, a speed code, and some not separated on the time line, an amplitude code, in which case the control system can be of the relay type, or of the proportional type,

with a reduced dynamic range, or (c) if all control and switching commands are not separated on the time line we can have a relay type, or a proportional-relay type control system for three movements: two proportional with a narrowed dynamic range, amplitude code, and one relay using a speed code.

Signals generated by one muscle can be used to control a great many SM when amplitude and speed codes are used. Here the switching signal for selecting and connecting the needed SM is supplied by the corresponding number of brief pulse trains, a speed code. An amplitude code is used to reverse the SM.

A speed code, or an amplitude code, may be used to connect the needed SM to the control system.

A nonresponse zone must be built into the system when switching is done by the same code used for control purposes. In this case the system is converted /133
to the mode for selecting the needed SM, to the nonresponsive zone, by supplying a signal, say a high-amplitude one. Once this is done the SM can be selected by a train of discrete signals of the same or different widths and amplitudes, or combinations of them. There are two ways the system can be converted to the control mode. One is automatic, upon lapse of a predetermined period of time, the other is to use a second train of high-amplitude signals. The switch should have one stable state for the former, two and more for the latter.

The bioelectric control systems discussed above for controlling several SM from one muscle use different types of switches, controlled from the same muscle, or by the same channel, than those used to control the SM. There are many cases, however, when the switches can be controlled from another muscle over an autonomous channel.

The switch can, for example, connect one of four SM by making amplitude selection of the command signal. The switch will have, for this purpose, a level damper and two electronic switches, one for the high, the other for the low, level. The switching cell will connect the corresponding SM depending on the combination of conditions of the latter.

System operation is as follows (wiring diagram Figure 3a). An electromiographic signal is supplied from the preamplifier to the envelope separation unit (diodes D_1, D_2, capacitors C_2, C_3, resistors, R_1, R_3), then to the level

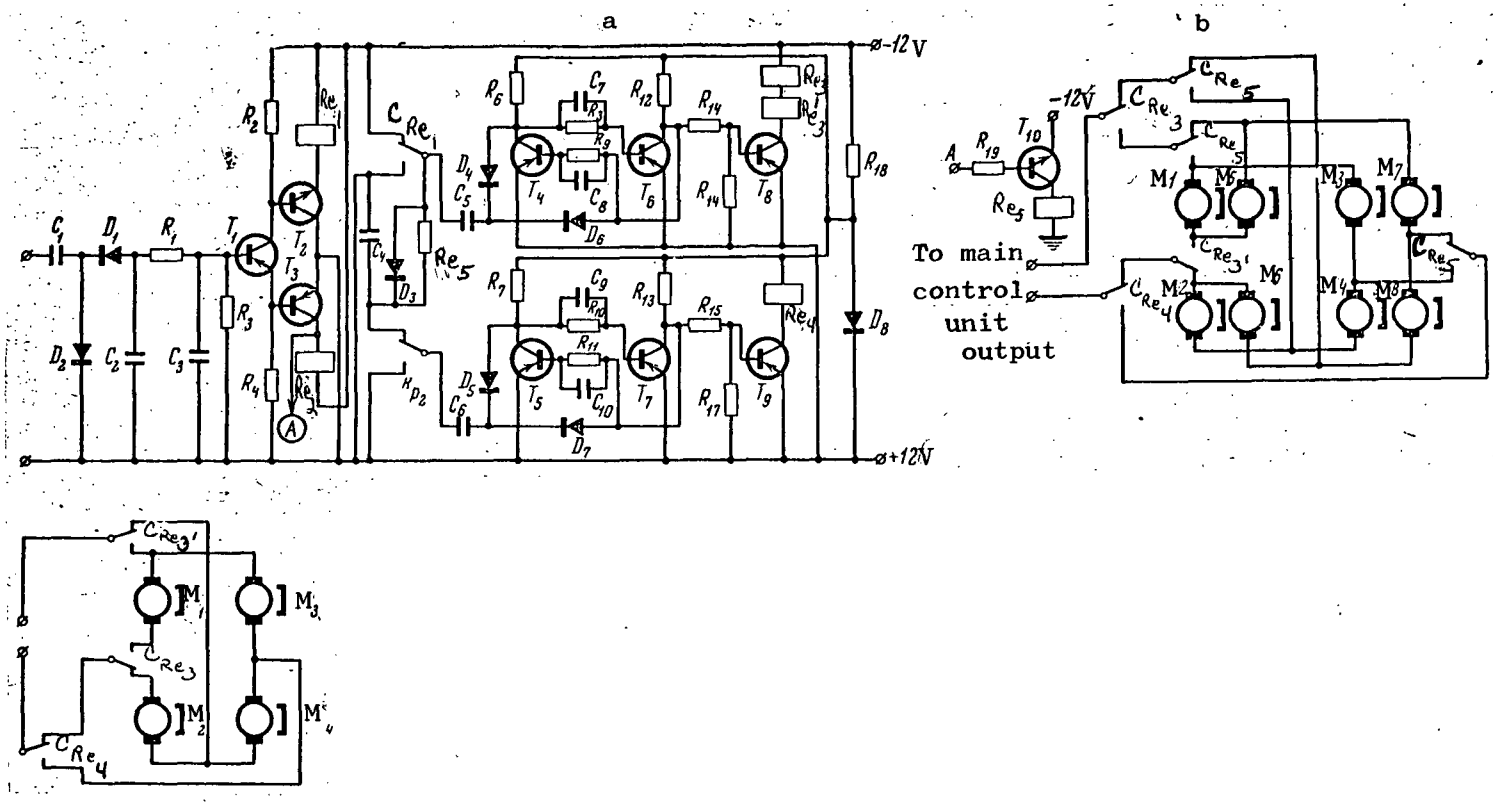


Figure 3. Switch wiring diagrams. a - four outputs; b - wiring diagram of a switch with eight outputs.

damper input (transistors T1-T3), the output stages of which are loaded respectively by two relays, Re_1 and Re_2.

A 0.5 V signal at the input causes relay Re_2 to operate, and both relays will operate when signal strength is 1 V. Operation of one, or both relays converts one, or both electron switches (symmetrical triggers with collector trigger) to the other stable state accordingly. The trigger controlled by the high level of the signal consists of transistors T4 and T6, that controlled by the low level of the signal of transistors T5 and T7. Relays Re_3, Re_3', and Re_4 are connected to the control channels of one of four SM, depending on the combination of trigger states. An interlock (C_4, D_3 and R_5) prevents the low level switch from operating when a high-amplitude signal is supplied.

A comparatively simple device, added to the above-described system, increases its functional potentials. Added to the system for this purpose is a switch with one unstable state (Figure 3b). This switch uses the same control channel (one muscle) but provides selective switching of twice as many reversible SM, as many as eight.

One of four SM (M_1 - M_4) in the first group can be connected to the control channels in a manner similar to that described. One of the four mechanisms in the second group (M_5 - M_8) can be switched, depending on the combination of stable states of the switches, when there is a control signal below the level of the first threshold (the operating threshold for relay Re_2) because this causes relay Re_5, with three groups of switching contacts, to operate. Relay Re_5 is connected to the collector circuit of transistor T10, supplied with a positive potential from the collector of transistor T3 (point A in Figure 3a).

Adding one unstable state to the switch permits the operator to obtain information on whether or not a slave mechanism in the first, or second, group /135 is connected to the output of the main control channels at a particular moment, regardless of whether or not a control signal is present.

The switch can be a device with two unstable states, in which case the amplitude selection principle can be used to control the switch. One SM can be connected to the system when there is no control signal, a second when the magnitude of the control signal is small, and a third when the magnitude is great. This system also provides the operator with information on which SM is connected to the control system.

We have, here, reviewed certain realization of a BECS with signals from one muscle. Even this quick review shows the variety of possible approaches to building systems for sequential control of several SM. The introduction into the system of even one source of biosignals can change SM control significantly, and what is even more important, qualitatively. Increasing the number of sequentially connected SM results in simultaneous control. So if there are two sources of control signals, the functions of SM control (C) and of switches (S) can be distributed between them in different ways:

TABLE

Variant	1	2	3	4	5	6
First muscle	C	C	C	S	S,S	S
Second muscle	C	S	C,S	C,S	C,S	S

Variant 1 is the simplest case: two muscles control one reversible SM. This is the most widely used practical approach to the bioelectric control method of building systems.

In variant 2 one muscle can only control the SM; the other is connected to the control system of the corresponding SM. One of the methods described above for switching with signals from one muscle can be used for this purpose. And switching can be accomplished at the same time as the SM control process is carried out.

The coding methods described above are quite varied, so the ways in which it is possible to realize them too are quite varied. It is preferable to use a conventional control system, that controlling two movements with two muscles, when but one SM is controlled. When one of the muscles has limited control capabilities (rapid fatigue, activeness low, dynamic range narrow), separation of control and switching between muscles can be desirable.

Variant 3 can be looked at in two ways:

(a) another control channel can be added to the system, one that uses control and switching by one muscle (the one reviewed above). The number of controlled movements now is increased by one, instead of two there are three, instead of four there are five, and so on. So the use of yet another source of signals is irrational. The system now has an additional channel, but system functionality has not, in essence, been increased. However, the possibility

of its use in certain cases cannot be excluded;

(b) we have a two muscle control system, and one muscle, in addition to control, performs the additional function of switching the entire system. The number of controlled movements now is twice what it was in analogous variant 2 systems. In this case the switching muscle can only use discrete codes because the continuous signal from this muscle can be used to control the SM.

Variant 4 can be used when the switching signals can be used to select a program, and then supply the command required to execute the program, for example. /136

Variant 5 is a more modern version of a two-muscle control system in which both muscles control and switch. All the virtues of any switching code, and combinations of such codes, can be utilized fully in this system. The amplitude selection principle can be used to build two-channel control systems providing independent (simultaneous) control of two pairs of movements, or the sequential control of eight movements, for example, by using different combinations of signals from the two muscles.

Finally, the switches in variant 6, as distinguished from those in variants 4 and 5, can use all switching codes (see the classification diagram), including the progressive code.

Logic switches with one and two stable states are most widely used today to control two pairs of movements with signals from two muscles [15-17].

There are different ways that control and switching functions can be distributed between several sources of control signals (three and more) when such are available and when using one of the coding methods described above. The possibilities for building control systems are tremendous in scope. Fifteen SM can be connected, for example, by combining bioelectric commands generated by four muscles [18].

If the number of possible combinations of commands exceeds the required number of slave mechanisms the "surplus" command combinations can be used for the simultaneous (parallel) control of two, or of several, SM.

The methods and principal solutions discussed above, realized and investigated in experimental bioelectric systems for controlling a considerable number

of SM with a limited number of sources of control signals, indicate the variety of possible approaches to the building of similar control systems.

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